INVESTIGATION 8-B

Measuring a Magnetic Field

TARGET SKILLS
- Performing and recording
- Analyzing and interpreting
- Communicating results

In this investigation, you will use a current balance to determine the strength of the magnetic field at the central axis of a solenoid.

Problem

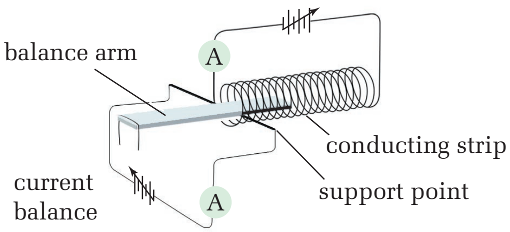
How can you measure magnetic field intensity with a current balance?

Equipment

- current balance and solenoid
- 2 variable power supplies (12 V DC)
- 2 DC ammeters
- electronic balance
- scissors
- string

Procedure

1. Set up the current balance-solenoid apparatus, as shown in the diagram.



2. With the power off, adjust the balance arm so that it is horizontal.
3. Turn on the power to the coil and balance arm. Adjust the polarity so that the conducting arm inside the solenoid is forced downward.

CAUTION The current in both the arm and solenoid can create enough heat to cause a burn.

4. Set and record the current in the solenoid to the upper range of its values. Set and record the current through the balance arm to the high end of its range, forcing down the balance arm inside the solenoid.
5. Loop a length of string over the outside end of the balance arm and, using scissors, adjust its length until the balance arm is horizontal.
6. Without changing any settings, turn off the current to both sources. Determine the mass of the string.
7. Keeping the solenoid current constant, repeat the experiment five more times, using a smaller balance current. Record the value of the balance current and the mass of the string each time.
8. Carefully measure
   - **(a)** the lengths of the solenoid and the current arm
   - **(b)** the number of turns in the solenoid
   - **(c)** the distance of the suspension point of the current balance to each of its ends (lever arms)

Analyze and Conclude

1. For each trial, use the mass of the string and the principle of levers to calculate the force acting down on the current arm. Record your data.
2. Draw a graph with the force acting on the current arm versus current in the current arm.
3. Describe the relationship between I and F when the magnetic field is kept constant?
4. Measure the slope of your graph. Use your data to determine the magnetic field, B, inside the solenoid.

Apply and Extend

5. Using your data and the equation below, calculate the strength of the magnetic field.

$$B = \mu_0 \frac{N \cdot I_S}{l}$$

$\mu_0 = 1.257 \times 10^{-6}\ \mathrm{T \cdot m/A}$, N is the number of turns in the solenoid, l is the length of the solenoid, and I_S the current flowing in the solenoid wire.

6. How did your two values for the magnetic field in the solenoid compare? What might cause them to differ?

Particle Accelerators

In the early part of the twentieth century, the development of the theory of the structure of the atom and its nucleus depended to a large degree either on the spontaneous disintegration of radioactive nuclei or on observations made when the products of those spontaneous disintegrations were directed at other nuclei. The particles emitted during natural disintegrations, however, such as the α-particles used by Rutherford in his experiments, provided only limited opportunity to observe nuclear reactions during bombardment. The particles were limited in energy and were emitted randomly in all directions, so they were difficult to harness in sufficient quantities to provide reliable results.

To overcome the difficulties of availability and reliability, particle accelerators were developed that were capable of emitting high-speed, subatomic-sized particles (protons, electrons) in sufficient numbers. Particle accelerators today are capable of accelerating charged particles to energies close to one million million electron volts, or 1000 GeV. This in turn has allowed physicists to investigate the fundamental composition of matter even more deeply, with the result that more and more fundamental particles are known to exist and complex models of the structure of matter have been developed. You will learn more about these models in Unit 5.

The Cockcroft-Walton Proton Accelerator

The first particle accelerator for use in nuclear research was built in 1932 by J.D. Cockcroft and E.T.S. Walton, students of Ernest Rutherford at the Cambridge Laboratory in England. In this accelerator, protons were introduced into the top of an evacuated glass tube and accelerated by using a potential difference between electrically charged metal cylinders. Since it is not possible to maintain a potential difference much more than 200 000 V between electrodes in an evacuated tube, Cockcroft and Walton used special multi-stage accelerator tubes, with each stage powered by a unique charging circuit. The protons accelerated by this arrangement approached energies of 1 MeV.

At the bottom of the glass tube, they placed a lithium target and consequently observed the first nuclear transformation caused by artificially accelerated particles. The bombardment of the lithium atoms with protons resulted in the formation of helium nuclei. For their work, Cockcroft and Walton were awarded the Nobel Prize in Physics in 1951.

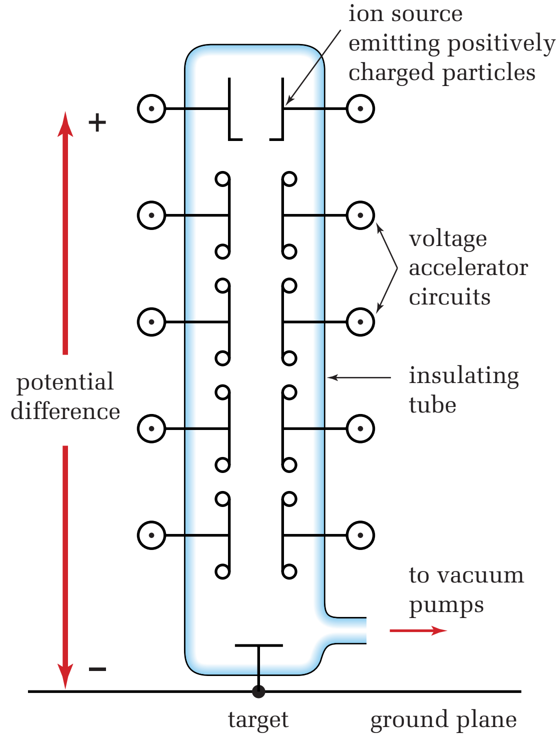


Figure 8.16 One type of multi-stage accelerator tube

The Cyclotron

To avoid the problems associated with very high voltages, Ernest O. Lawrence and his colleagues at the University of California at Berkeley designed an accelerator based on a circular path that subjected the charged particles to a large number of small increases in potential. This was achieved by the use of a pair of evacuated hollow semicircular chambers (called "dees," because they are shaped like the letter D). The charged particles are injected into the chambers at the centre. This device is called a **cyclotron**.

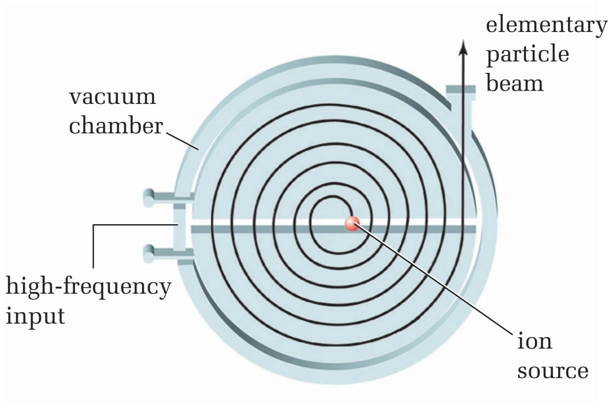


Figure 8.17 A cyclotron

The dees are positioned between the poles of an electromagnet that provides a uniform magnetic field perpendicular to the path of the charged particle inside the chamber, thus causing its circular motion. A potential difference is applied between the two chambers, so that as the charged particle crosses from one chamber to the next, it will be accelerated by the potential difference. The particle will speed up and, as a result, the radius of its path will increase. In order for the particle to speed up when it crosses the gap between the dees again, the direction of the potential difference must be reversed. This alternating potential difference is kept in phase with the frequency of orbit of the charged particle so that it will always speed up when it crosses the gap between the chambers. Consequently the particle will spiral outward until it reaches the outer edge of the dee, where a magnetic field is applied to deflect the particle out through a gate and onto a target. The first cyclotron built in 1931 produced ions of energy 80 keV, but by the latter part of that decade, energies of 30 MeV were quite common.

As you will learn in Unit 5, when particles reach speeds close to the speed of light, relativistic effects become prominent. In the case of the cyclotron, the mass of the particle increases to such an extent that it becomes necessary to synchronize the alternating potential difference with the time of travel of the particle.

The Synchrocyclotron

In the **synchrocyclotron**, an adaptation of the cyclotron, the frequency of the accelerating electric field, applied between the dees, is adjusted to allow for the relativistic increase in mass of the particles. Since the change in frequency required takes approximately 10 ms, the ions are delivered in small bursts, rather than continuously. This results in the intensity of the ion beam being lower than the conventional cyclotron. This is compensated for by using larger magnets, although cost then becomes a limiting factor.

The Betatron

The principle of the cyclotron has been adapted to allow for the acceleration of electrons. Since electrons were historically called "beta particles," the accelerator is called a **betatron**. Instead of allowing the electrons to spiral outward, a magnetic field applied along the central axis of an evacuated doughnut is uniformly increased. This increasing magnetic field induces an electric field that causes the electron to speed up but retain the same radius, inside the doughnut.

The Linear Accelerator (LINAC)

New **linear accelerators** differ from earlier machines, such as the Cockcroft-Walton accelerator, in that they use electric fields alternating at radio frequencies to accelerate the particles, rather than high voltages.

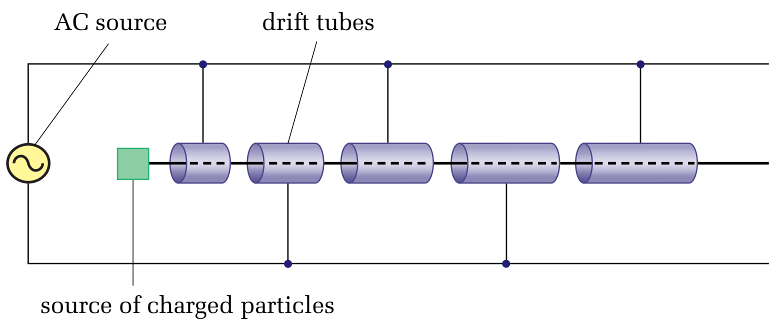


Figure 8.18 Schematic of a linear accelerator

The acceleration tube consists of many individual drift tubes that are charged alternately positive and negative. When a positive particle enters the tube, if the first drift tube is negative, it will attract the particle. Inside the tube, there is no electric field, so the particle "drifts" through at constant speed. If the electric field is reversed as the particle leaves the first tube, it will accelerate toward the second drift tube and enter it at a higher speed. This second tube is longer and the particle will leave it just as the potential reverses and it will be attracted to the third drift tube. Hence, the particle is accelerated between a long series of drift tubes. The Stanford Linear Accelerator Centre linear accelerator is

3.2 km long, contains 240 drift tubes, and is designed to accelerate electrons to energies above 20 GeV.

Synchrotron

A very efficient way to accelerate protons is to combine the features of the cyclotron and the linear accelerator. Such a device is the **synchrotron**.

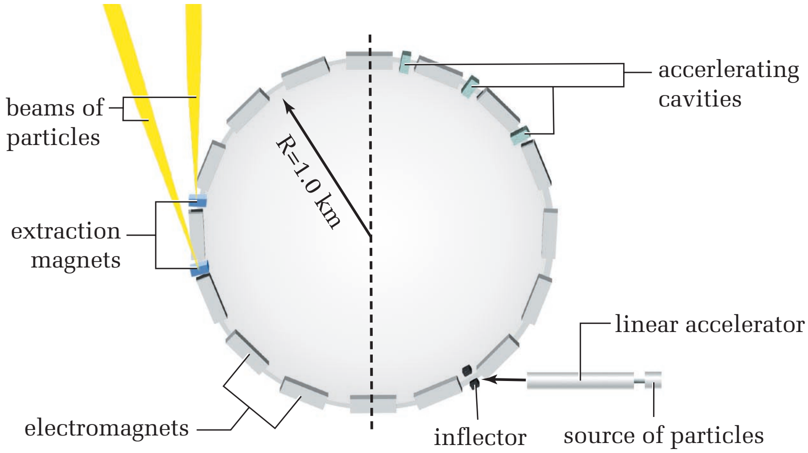


Figure 8.19 A synchrotron

Since a magnetic field is required only to maintain the circular orbit, rather than use one large central magnet, a series of ring magnets surrounding a doughnut-shaped vacuum tank is used, making the synchrotron much more economical. At repeated locations along the circular path, high-frequency accelerating cavities (much like short linear accelerators) are inserted to accelerate the protons. This combined technique produces protons of enormous energy that can in turn be directed at other targets and the resulting fundamental particles can be investigated. In 1954, Lawrence, the designer of the cyclotron, developed a synchrotron that produced protons with energies in the range of 6.2 billion electron volts. It was therefore called the "bevatron." (Today, it is identified as 6.2 GeV.) These protons were in turn used to discover the antiproton.

Other renowned synchrotron installations include the 1.0 TeV Tevatron at Fermilab (the Fermi National Accelerator Laboratory) in Illinois and the 400 GeV at CERN (European Council for Nuclear Research) near Geneva, Switzerland.

The Tokamak Fusion Test Reactor

An international group, International Thermonuclear Experimental Reactor (ITER), which includes Canada, is attempting to develop efficient nuclear fusion reactors, in which two isotopes of hydrogen (deuterium and tritium) collide with such high energy that they "fuse" to produce a helium nucleus, and at the same time release enormous amounts of energy. Fusion can occur only at

temperatures equivalent to the centre of stars, about 10^8 °C. At these temperatures, the fusion reactants actually break down into individual positive nuclei and negative electrons. This ionized gas is called a "plasma." It is because these ions are charged that it has been found both possible, and necessary, to confine them within a toroidal (doughnut-shaped) magnetic bottle, since no material bottle can exist at such high temperatures for its containment.

WEB LINK

www.mcgrawhill.ca/links/physics12

For an award-winning photograph taken inside a Tokamak reactor, go to the above Internet site and click on **Web Links**.

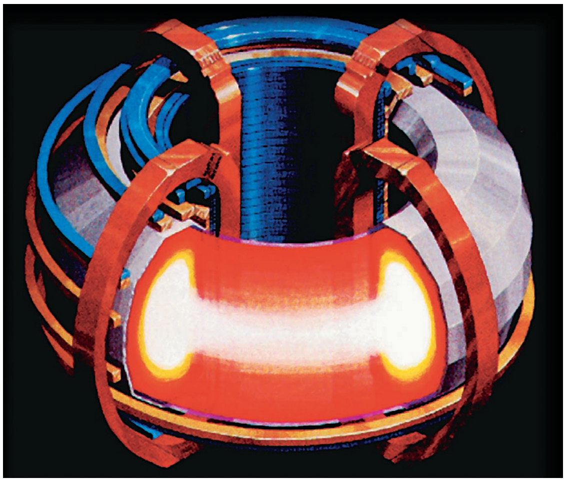


Figure 8.20 The Tokamak fusion test reactor

This magnetic confinement seems to have the greatest potential and its popular design is based on the Tokamak system, developed in the former U.S.S.R. ("Tokamak" is an acronym for the Russian translation of "toroidal magnetic chamber.")

8.3 Section Review

1. K/U
   - (a) Under what conditions will a charged particle be subject to the maximum possible deflecting force when entering a magnetic field?
   - (b) Under what conditions would the deflection be minimal?
2. K/U In what way is the force acting on a conductor carrying a current in a magnetic field similar to the deflecting forces described in question 1?
3. C Prepare a report or other presentation describing the many applications of the deflection of a charge by a magnetic field. Give a detailed account of the social significance of one of these applications.
4. K/U Explain how a particle accelerator and velocity selector complement the operation of a mass spectrometer.
5. MC In 2001, Canada and Japan were competing for the right to build a Tokamak-style fusion reactor. Canada's plan is to locate the reactor in Clarington, Ontario, adjacent to the Darlington nuclear plant. Research Canada's bid and make a presentation in which you
   - (a) outline the reasons Canada's ITER team had for wanting to build the reactor
   - (b) explain why that particular location was chosen
   - (c) give your own opinions on the merit of the plan